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Fermilab

ACCELERATOR DIVISION CAPACITOR STORED ENERGY DEVICES

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An attempt has been made to list all devices in the Accelerator Division that use energy storage capacitors. Safety requirements as stated by the National Electrical Code (NEC) are considered and recommendations for safe practices are listed.

1. Code Requirements, NEC 1978, Article 460

1.1 Capacitors containing more than 3 gallons of flammable liquid are to be stored in vaults or outdoor fenced enclosures.

1.2 Capacitors are to be enclosed, located or guarded so that accidental contact is not possible, unless the area is only accessible to authorized and qualified persons.

1.3 Isolating means are required for capacitors that will be removed from service. The isolation measure is to provide a visible gap in the electrical circuit.

1.4 Overcurrent protection is required to detect and interrupt fault current that is likely to cause dangerous pressure within an individual capacitor.

1.5 Identification is required. Nameplate information to include: manufacturer
frequency
KVAR or amperes
number of phases
amount of liquid
flammable or non-flammable

1.6 A means of discharge is required to reduce the residual voltage to 50 volts or less:

within 5 minutes if initial voltage is over 600 volts

within 1 minute if initial voltage is less than 600 volts.

2. Discharging Capacitor

The stored energy in a capacitor is $W = \frac{1}{2}CV^2 = \frac{1}{2}QV$ with

C in farads

V in volts

Q in coulombs

W in Joules (Wattsec)

When a capacitor, initially charged to a voltage V_o, is discharged through a resistance R, the discharge current at first instance is $V_o = -V_o/R$. Thereafter the current varies according to $i = i_o E^{-t/RC}$. The charge on the capacitor decreases during discharge according to $q = Q_o E^{-t/RC}$, where Q_o is the initial charge. The National Electric Code states that the residual voltage is to be reduced to 50 volts within 1 minute for $V_o < 600$ volts and within 5 minutes for $V_o > 600$ volts. Since $V = Q/c$, the voltage at discharge follows the same curve as the charge, or $v = V_o E^{-t/RC}$. From this we can find the resistance necessary to meet the code requirement for discharge time.

$$\frac{v}{V_o} = E^{-t/RC}$$

$$\ln \frac{v}{V_o} = -\frac{t}{RC}$$

$$\ln \frac{V_o}{v} = \frac{t}{RC}$$

$$R = \frac{t}{C \ln \frac{V_o}{v}}$$

with $t = 60$ sec for $V_o < 600$ volts

$t = 300$ sec for $V_o > 600$ volts

V_o = peak operating voltage

$v = 50$ volts

If a capacitor bank already has a discharge resistor connected, we can find the discharge time from:

$$t = RC \ln \frac{V_o}{v}$$

All capacitor banks in the Accelerator Division have been listed with their voltage, capacitance and stored energy. Values of discharge resistance required per NEC are listed together with the discharge times.

Warnings

1. In order to meet the NEC requirement for overcurrent protection it is customary practice to use fuses to protect either individual capacitor cases or complete capacitor banks. If a fuse blows and the capacitor has internal discharge resistors, the capacitor will automatically discharge. If a fuse blows and the capacitor has no internal discharge resistor, which is very often the case, the capacitor will stay charged.
   If a blown fuse is detected, always discharge the capacitor, short it and ground it.
2. In general a capacitor does not return, on discharge, the full amount of energy put into it. Some time after the discharge an additional discharge may be obtained. This phenomenon is known as dielectric absorption. Before working on a device with capacitors, first discharge it, leave the discharge device on it, short and ground the capacitors. Leave the capacitor shorted and grounded during the complete servicing time.

3. When storing and transporting capacitors, always have the capacitors shorted.
4. An impulse discharge of ¼ Joule causes muscular contraction. An impulse discharge of 50 Joule is lethal (ref. 1).
5. If no good contact is made with the discharging device, it is possible to create welding of the discharge device to the stored energy device. See Appendix A.
6. Some capacitors are located in radiation areas, so radiation rules need to be observed in addition to all other safety rules.
7. Many capacitors use askarel as the liquid dielectric. The principal constituent of askarel is PCB (polychlorinated biphenyl) a toxic substance with adverse ecological effects. These capacitors should be marked with a sticker, indicating that they contain PCB.

   When a PCB filled capacitor fails, it has to be disposed of in accordance with PCB disposal requirements.
8. Whenever a system has been subjected to a hi-pot test, it should be treated as a charged capacitor. Proper discharge techniques are to be followed prior to working on the system, see also Appendix B.

SAFETY

Capacitors are a potential shock hazard, explosion hazard, fire hazard and toxicity (PCB) hazard.

Shock Hazard

1. Before working on capacitors, always remove power from the capacitors by a visible disconnect.
2. After disconnecting the power, the capacitors still present a potential shock hazard due to the fact that a charge may still be existing. The capacitors should be discharged prior to handling.

   Some systems have a mechanical automatic discharge system.
   Some capacitors have internal discharge resistors.
   Under no condition shall these discharge devices be considered as adequate. As stated by NEMA Publication No. CP-1-1976, "The use of a discharge device is intended to supplement rather than to displace the short-circuiting of a capacitor unit before handling".
3. After disconnecting the capacitor from the power source, wait at least 5 minutes, then short and ground the capacitor equipment and individual capacitors, using an insulated ground stick. Shorting should be terminal to terminal and terminal to case. Individual units should also be shorted because shorting of a complete capacitor bank is ineffective in case of a fuse operation or other disconnection of an individual capacitor unit.
4. Ground sticks should have a discharge resistor so that initial discharge of the capacitors is through a resistor (see attached SKMS81375). The discharge resistance as required by the National Electric Code requirements is listed for the different equipments.

Westinghouse, for their Wemcol impregnated capacitors (ref. 4) suggests using a resistance in ohms about equal to the maximum peak voltage that may have been on the capacitor. The resistor should have a peak voltage capability greater than the maximum peak voltage on the capacitor and an energy capability greater than the energy stored in the capacitors.

5. After discharging the capacitors, a shorting connection should be installed between the terminals and a ground connection should be left on till all work on the equipment is completed.
6. If an insulated wire is used from ground stick to ground, it should have clear insulation, so that wire continuity is visible.
7. Ground sticks should always be kept clean!

Explosion Hazard

Capacitors, fused or unfused, may rupture upon failure. They may explode also during hi-pot tests; it is therefore important that the capacitors are installed or shielded in such a way that personnel are protected from exploding capacitors.

Sometimes capacitors show bulging due to internal pressure from gassing. These capacitors should be disposed of. It is also recommended that the internal pressure be relieved before handling by breaking off a bushing terminal with a long pole, or by puncturing the case with a punch after covering the capacitor with a heavy cloth. The puncture should be made where a minimum of fluid leakage will occur. Provisions should be made to collect the drained fluid.

Avoid liquid contact with skin and eyes and avoid exposure to fumes in an unventilated area.

Fire Hazard

A fire hazard exists where a flammable dielectric fluid is used in the capacitors. This should be stated on the nameplate. The location of these type capacitors should be such that a possible fire after capacitor failure and rupture can be contained in accordance with the National Electric Code.

Conclusion

There are a large variety of devices with capacitive stored energy in the Accelerator Division.

Many of the devices have automatic discharge equipment. There are a variety of discharge and grounding sticks in use. The Safety Department is in the process of procuring grounding sticks.

Due to the variety of the different systems, it is not possible to treat each system alike. It is recommended that the persons responsible for the different systems write their own safety discharge and grounding procedures based upon the general recommendations as listed in these guidelines. Several of the accelerator systems have existing written procedures with pictorial guides. This would be a good overall system, very valuable for training of new people.

JR/nep

Appendix A

Welding of the grounding stick to the capacitor can occur depending on capacitor energy. A large amount of stored energy should be discharged using the proper discharge resistance and using positive contact procedure. Intermittent contact will initiate welding.

The amount of energy needed to heat and weld 1 cc of copper can be found as follows:

Copper: melting point = 1083 C

specific heat = .092 cal/g/°C at 20°C

Latent heat of fusion = 49 cal/g

Density = .3223 lb/in^3

The temperature rise to the melting temperature $\Delta T = 1083-20 = 1063°C$.

To heat one gram of copper to melting temperature, it takes

$$.092 \times 1063 = 97.8 \text{ calories}$$

To melt 1 gram of copper, takes 49 calories

To heat and melt 1 gram of copper it takes 146.8 calories.

One cubic inch of copper weighs .3223 pounds = .3223 x 453 = 146 grams

1 cm^3 of copper weighs $\frac{146}{(2.54)^3} = 8.9$ grams.

To heat and melt 1 cm^3 of copper takes: 146.8 x 8.9 = 1308 calories.

1 Joule $\approx$ .239 calories

In order to heat and melt 1 cc of copper, it will take $\frac{1308}{.239} = 5473$ joules

A discharge of 5.5 kJ can cause melting of 1 cm^3 of copper, which would mean welding of the grounding rod to the energy storage system. The same calculations for steel show that 4.3 kJ is enough to heat and weld 1 cc of steel.

A typical weld with a spot diameter of .5 cm and a penetration of one-fifth the spot diameter, corresponds to heating and melting of .040 cc. of metal.

The average cold resistance of a spot this size is .5 milliohm (ref. 3).

This weld would be accomplished with an energy .04 x 5473 = 220 Joules.

If this energy is discharged in .1 second, the average power would be 2200 Joules per second or 2200 watts. From $P = i^2R = \frac{V^2}{R}$ we find that the welding current will be $\sqrt{\frac{2200}{.5 \times 10^{-3}}} = 2080$ amps at a voltage of 1 volt across the weld.

Appendix B

Capacitance of Cables

The capacitance of a one-conductor shielded cable is given by the formula $C = \frac{7.35(SIC)}{\log \frac{D}{d}}$

where C = capacitance of the cable in picofarads per foot

SIC = dielectric constant of the insulation

D = diameter over the insulation

d = diameter under the insulation

typical values of SIC

polyvinyl chloride (PVC)	5.0 - 8.0
butyl and EP insulation	3.5
polyethylene insulation	2.3
cross-linked polyethylene	3.5 - 6.0

A typical example is our 13.8 KV feeder cable, 750 MCM with cross-linked polyethylene insulation.

Typical length is ½ circumference of the main ring, or

10600 feet

D = 1.45"

d = 1.1"

$$C = \frac{7.35 \times 5}{\log \frac{1.45}{1.1}} = 306 \text{ pf/ft}$$

for 10,600 ft., C = 3.27μf

At the typical test voltage of 29 KVDC, the feeder has a stored energy of 1362 Joules.

To discharge the feeder in accordance with the National Electric Code to 50 volts in 5 minutes, requires a discharge resistor of 15 MΩ.

DEVICES WITH CAPACITIVE ENERGY STORAGE

MAIN RING

DEVICE		CAPACITANCE C µf	PEAK VOLTAGE V VOLTS	STORED ENERGY $\frac{1}{2}CV^2$ JOULES	NEC Required Discharge Resistance KΩ	NEC Required Discharge Time t Sec	REMARKS
RF Anode Supplies		45	34,000	26010	1022	300	
RF	uc	4	480	.46	6631	60	
Modulators	amp	.1	30,000	45	470,000	300	oil filled
Cap. Tree per phase		2940	12,000	212000	18.6	300	
C48 Kicker		.080	200 KV	400	493000	300	
B24 Pulsed Quad		240	2000	480	340	300	
E48 Pinger		240	2000	480	340	300	
C34 Pulsed Quad		240	2000	480	340	300	
A34 Pulser		240	2000	480	340	300	
F13 Pulsed Quad		240	2000	480	340	300	
RF Test Station		11	35000	6700	4160	300	
Harmonic Filter		25	8000	800	2364	300	
Power Supplies Passive Filter		200	1000	100	500	300	
ϕ Power Supplies Active Filter		690000	40	552		60	ex. 50Ω disch. res.
A_o Power Supplies (2)		88800	150	999	60	60	ex. 33Ω disch. res.

DEVICES WITH CAPACITIVE ENERGY STORAGE

BOOSTER

DEVICE		CAPACITANCE C µf	PEAK VOLTAGE V VOLTS	STORED ENERGY $\frac{1}{2}CV^2$ JOULES	NEC Required Discharge Resistor R KΩ	NEC Required Discharge Time t Sec	REMARKS
200 MeV Chopper		.17	1000000	850	232000	300	ex. 1000 KΩ disch. res.
S1 and S2 Pulsed Power Supplies		1200	1.300	1014	76	300	ex. 75 KΩ disch. res.
Electrostatic Injection Inflector		.04	70000	98	1035000	300	ex 100 KΩ disch. res.
ORBUMP Supply H^+		2400	2250	6075	33	300	
ORBUMP Supply H^-		1100	3500	6738	64	400	
Hor & Vert Notch Power Supply		.34	32000	174	137000	300	ex. 100 KΩ disch. res.
Bex Back		1660	350	102	19	60	
GMPS Circuit Cap, Each Girder		8300	1000	4150	12	300	
GMPS Filters		2800	1000	1400	36	300	oil filled
East and West RF Anode Supplies		45	34000	26010	1022	300	
RF Modulators	ac-	4	480	.46	6631	60	
	output-	.1	30000	45	470000	300	oil filled
MK 90	cable	.075	60000	135	564000	300	
	internal	.15	60000	270	282000	300	
MP 01 Pulsed Septum		2400	1500	2700	37	300	
MKS 01/	cable	.075	50000	94	579000	300	
MKS-02	internal	.15	50000	198	289500	300	
RF Test Station		11	3500	6700	4160	300	
MP-70		2400	1500	2700	37	300	

DEVICES WITH CAPACITIVE ENERGY STORAGE

SWITCHYARD

DEVICE	CAPACITIVE C μf	PEAK VOLTAGE V VOLTS	STORED ENERGY $\frac{1}{2}CV^2$ JOULES	NEC Required Discharge Resistor (max) R KΩ	NEC Required Discharge Time (max) t (sec)	REMARKS
MK-120	240	2000	480	340	300	
MV-T90 inv	970	415	84	29	60	
MVT-101 inv	970	415	84	29	60	
MVT-120 inv	970	415	84	29	300	
PVT-90	240	2000	480	339	300	
PVT-91	240	2000	480	339	300	
PVT-101	240	2000	480	339	300	
PVT-103	240	2000	480	339	300	
Pos. Pulse	480	2000	960	169	300	
Ang. Pulse	480	2000	960	169	300	
EXT	60800	400	4864	.475	60	

DEVICES WITH CAPACITIVE ENERGY STORAGE

LINAC

DEVICE		CAPACITANCE C µf	PEAK VOLTAGE V VOLTS	STORED ENERGY ½CV² JOULES	NEC Required Discharge Resistor (max) KΩ	NEC Required Discharge Time (max) sec	REMARKS
PA Modulators	bias supply	220	2700	800	340	300	ex. disch. resistor 140 KΩ
	plate	100	6500	2100	600	300	ex. disch. res 200 KΩ
4616 Anode Supply	driver	24	20000	4800	2086	300	aut gnd 1KΩ to 0Ω
	screen	40	3500	245	1765	300	aut gnd 25KΩ
7651 Anode Supply		40	3000	180	1832	300	aut gnd 25KΩ
Quad Supplies	C1-C4	2200	800	704	49	300	aut gnd 100Ω
	C11-C22	240	800	77	451	600	aut gnd 100Ω
Both Haeflies		.005	750000	1406	6240MΩ	300	
HV PS Cap Bank		30.8	52000	41640	1402	300	aut gnd 2.5KΩ to 0Ω
PFN Power Bank		1000	600	180	24	60	
PFN Turn-Off Supply		20	2000	40	4066	300	
Ion Pump Power Supply		2	5000	25	32600	300	
Varian p.s. for ion pump		.5	10000	25	113MΩ	300	ex. 10MΩ disch. res.
Triplet p.s.		360000	40	288	--	60	ex. 4Ω disch. res.
Chopper U.V.		.27	30000	122	174MΩ		aut gnd 4000MΩ to 0Ω
H^- Extractor		.1	30000	45	469MΩ	300	ex. 270KΩ disch res +2.5MΩ solenoid
H^+ Extractor		.048	12000	.24	1100MΩ	300	ex. 333MΩ disch res safety ckt 10MΩ
HV p.s. (anode supply)		8	8000	256	7400	300	ex. 30KΩ disch res
Arc modulator		3900	300	176	8.6	300	
Cup pulser		900	600	162	27	300	ex. 47KΩ disch res
		1800	300	81	19	300	ex. 47KΩ disch res

REFERENCES

1. ZGS Safety Information - December 10, 1964.

2. National Electric Code - 1978.

3. Welding for Engineers, J. Wiley.

4. Westinghouse Publication I.L. 39-311-1A.

5. NEMA CP-1, 1976.

6. Ten Commandments of Electronic Safety.

7. Okonite Bulletin 721.1.

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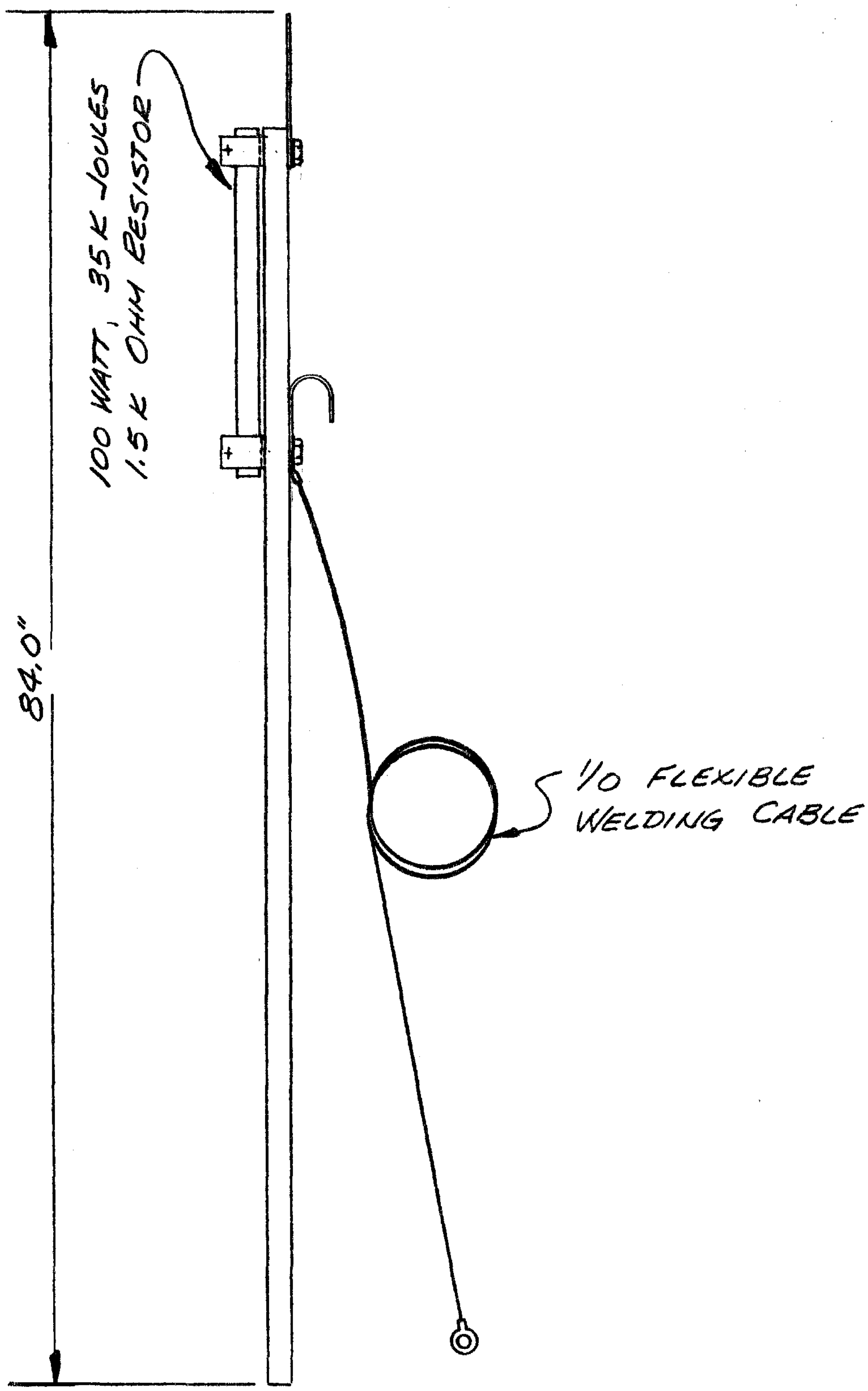

Westinghouse Electric Corporation

TITLE MANUAL GROUNDING STICK

SKMS81375

DIV & PLANT LOCATION—DAD—BLOOMINGTON, IND. U.S.A.

SAFETY INFORMATION

TITLE

ELECTRIC SHOCK, SEVERITY FACTORS

(60 Cycle, 120 Volt Alternating Current)

TM-851

The severity of the shock received when a person becomes part of an electrical circuit is affected by three primary factors. These factors are:

(1) The rate of flow of current through the body, measured in milliamperes;
(2) The path of current through the body; and
(3) The length of time the body is in the circuit.

Other factors which may affect the degree of shock are: the frequency of the current, phase of the heart cycle when shock occurs, and the physical and psychological condition of the person. The following are measurements of injury related to current for the case of 60 cycle, 120 volt alternating current.

Less than 1/2 milliampere	--	No sensation.
1/2 to 2	--	Threshold of perception.
2 to 10	--	Muscular contraction (mild to strong).
5 to 25	--	Painful shock, inability to let go.
Over 25	--	Violent muscular contraction.
50 to 100	--	Ventricular fibrillation.
Over 100	--	Paralysis of breathing.
<u>Direct Current Voltage</u>		
60 milliamperes	--	Muscular contraction.
500 milliamperes	--	Lethal.
<u>Impulse Discharge</u>		
1/4 joule	--	Muscular contraction.
50 joule	--	Lethal.

Over 100, 000 cycles there is no sensation to shock but strong possibility of burns.

In estimating possible body current, assume a 500 ohm body resistance between major extremities. This low figure might be attained when the skin is initially injured by shock from voltages as low as 50 Volts or from damp contact conditions.

<u>Example</u>: 50 Volts A. C. divided by body resistance of 500 ohms, equals 100 milliamperes, which is lethal if through body.

Ref: Los Almos, <u>Electrical Safety Guide</u>; <u>Safety In Industry</u>, Bulletin No. 216